2021 IEEE India Geoscience and Remote Sensing Symposium (InGARSS)

Proceedings

6 - 10 December 2020
Virtual Symposium

IEEE Catalog Number: CFP21U63-ART
ISBN: 978-1-6654-4249-7

2021 IEEE International India Geoscience and Remote Sensing Symposium (InGARSS) | 978-1-6654-4249-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/InGARSS51564.2021.9792077

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Sponsored by

The Institute of Electrical and Electronics Engineers
Geoscience and Remote Sensing Society

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2021 IEEE International India Geoscience and Remote Sensing Symposium (InGARSS) | 978-1-6654-4249-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/InGARSS51564.2021.9792019

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2021 IEEE International India Geoscience and Remote Sensing Symposium (InGARSS) | 978-1-6654-4249-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/InGARSS51564.2021.9791867

FOREST STAND HEIGHT ESTIMATION BY INVERSION OF POLARIMETRIC CANOPY SCATTERING MODELS

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ABSTRACT

Physical scattering models can be employed for estimating propagation and attenuation of electromagnetic waves through forest canopies. With polarimetric SAR (PolSAR) data (including dual-pol data, by simplifying assumptions), we have enough information to suitably invert these models to estimate important biophysical forest parameters, such as the vegetation stand height. This paper successfully attempts the estimation of forest stand height using two microwave canopy scattering models, viz., single-scattering radiative transfer model and the dielectric cylinder model (with a common rough surface scattering model). The ground measurements were taken from the study area in the Western Ghats region of Kerala. Iterative Optimization method was used to invert the non-linear models and the height of trees were retrieved using dual-pol data from ALOS-2 satellite, over the test sites. The accuracy of model derived heights was estimated by comparing them to the heights of trees measured in-situ. The results indicated that the inversion of the dielectric cylinder model perform better, yielding a coefficient of determination (R^2) of 0.61 and a root mean square error (RMSE) of 3.16 m. The single scattering model produced relatively lower R^2 value of 0.47.

Index Terms— Canopy Scattering Models, Vector Radiative Transfer Modeling, Dielectric Cylinder, Biophysical Parameter

1. INTRODUCTION

Knowledge on biophysical properties of tropical forests retrieved from remote sensing data enables to improve monitoring of these unique areas, very often impenetrable. In particular, the use of Synthetic Aperture Radar (SAR) for monitoring forests has drawn a great attention in the past decades due to its ability to observe earth surface at all weather conditions and sensitivity to the dielectric and geometrical properties of size, shape and orientation of scattering elements. Because of the randomly oriented complex geometries of the various scattering particles, the radar scattering from natural earth surfaces involves complicated electromagnetic wave interactions.Therefore, it is impossible to deal with all kinds of possible earth elements configurations and conditions in a single polarimetric radar scattering model for a vegetation layer over earth surfaces. Hence researchers attention was always focused on the development of approximate scattering models [1][2]. Many microwave scattering models have been developed to better understand the interaction of microwave signals with forests and other vegetated targets, and thereby to assist in forest parameter retrieval from synthetic aperture radar (SAR) measurements [1][3][4][5][6][7].

It is well known that the backscattering coefficient is not only affected by the radar system parameters such as frequency, polarization, and incident angles, but also the surface parameters such as soil roughness and moisture, and presence and structure of vegetation. Hence, accurate modeling of the propagation of microwaves through tree foliage is generally difficult due to the complexity of the tree electromagnetic geometry and its constituent elements, e.g. trunk, branches, and leaves, where dimensions are comparable to the microwave signal wavelength over a wide range of frequencies. Despite its complex nature, the canopy volume has been treated in the literature as a homogeneous mixture of discrete, randomly distributed and oriented dielectric disks and cylinders representing leaves and branches or trunks respectively [1][8].

Tree height is one of the important parameters for estimating Above Ground Biomass (AGB). Chave et al. reported that the addition of tree height can improve the efficiency of allometric models [9]. Lima et al. compared six allometric models and concluded that an allometric model including tree height had had the highest R^2 [10]. The purpose of this paper is to show how the dual-pol ALOS-2 L-band data can be exploited to yield more accurate tree heights of the selected vegetation stands with the use of two canopy scattering models viz., the single-scattering radiative transfer model with Rayleigh particles and the defoliated trunk layer approximated as dielectric cylinder layer of finite length. Both these layers are sitting on a rough surface layer modeled using the state-of-the-art I^2EM model.

2. METHODOLOGY FOR HEIGHT ESTIMATION USING CANOPY SCATTERING MODELS

Of the available scatter models, we focused on single-scattering radiative transfer model with Rayleigh particles [11], and the model developed with reference to the model proposed by Karam and Fung [12]. These models, respectively referred to as Model I and Model II in this study, are both based on the vector radiative transfer theory (VRT) and were developed for microwave backscattering studies. A brief discussion is given in the following section regarding the geometrical description of the medium, the electromagnetic modelling of the signal–canopy interactions, the input parameters, and the output data. All the modeling and simulations were carried out using custom code in Python3 language whereas ALOS-2 data processing was carried out using ArcGIS software.

2.1. Model I: I^2EM + S^2RT

In this model, the vegetation is divided into two layers: the canopy layer, mainly includes the stems and leaves, and the ground layer includes the rough ground. Backscattering from the rough ground is modeled with Improved Integral Equation Method (I^2EM model). To compute the scattering at the diffuse air-canopy boundary, the model represent the canopy in terms of an equivalent, homogeneous dielectric medium. The total single-scattering backscattering coefficient is the sum of the four backscattering contributions. These contributions include: (a) single backscattering by the ground surface, (b) single direct backscattering by the canopy elements, (c) a combination of single bistatic scattering by the ground followed by single bistatic scattering by vegetation elements or the reverse sequence and (d) transmission through the canopy, to specular reflection by the ground surface, followed by backscatter by the vegetation volume, followed by another specular reflection by the ground surface.

$$\begin{aligned}\sigma^0_{pq} &= \sigma^0_{g_{pq}} + \sigma^0_{c_{pq}} + \sigma^0_{cgt_{pq}} + \sigma^0_{gcg_{pq}} \\ &= \gamma_p\gamma_q\sigma^0_{s_{pq}}\theta_i + 4\pi\cos\theta_i\frac{1-\gamma_p\gamma_q}{K^p_e+K^q_e}\frac{3K_s}{8\pi} \\ &\quad + 4\pi\cos\theta_i\gamma_p\gamma_q\Gamma^p\Gamma^q\frac{1-\gamma_p\gamma_q}{K^p_e+K^q_e}\frac{3K_s}{8\pi} \\ &\quad + 4\pi\cos\theta_i\frac{H\gamma_p\gamma_q}{\cos\theta_i}\left(\frac{2\Gamma^p\Gamma^q}{\cos\theta_i}\right)\end{aligned} \quad (1)$$

Equation (1) referred is the S^2RT model with rayleigh scatterers under incoherent addition assumption, where $a = \frac{K_s}{K_e}$ is the single scattering albedo, H is the height of the medium.

2.2. Model II: I^2EM + Dielectric cylinder layer

In model II, the medium is subdivided into a layer of defoliated vegetation as a collection of randomly oriented dielectric cylinders of finite length and the underlying rough ground. The scattering amplitude and the extinction cross-section of an arbitrarily oriented single cylinder are calculated. The total backscattering coefficient is the sum of the two backscattering contributions including scattering from the randomly oriented cylinder layer and from the underlying surface. The first order solution of the radiative transfer equation is used to obtain the backscattering coefficient,which can be written as:

$$\sigma^0_{pq}(i) = \sigma^0_{c_{pq}} + \sigma^0_{g_{pq}} \quad (2)$$

where $\sigma^0_{c_{pq}}$, $\sigma^0_{g_{pq}}$ represents backscattering from the canopy and ground respectively.The backscattering coefficient due to the cylinder layer, $\sigma^0_{c_{pq}}$, can be written as [12]:

$$\begin{aligned}\sigma^0_{c_{pq}} &= [4\pi\cos\theta_i/\langle K^p_e(i)\rangle + \langle K^q_e(i)\rangle] \\ &\cdot\{1 - exp\left[-\left(\langle K^p_e(i)\rangle + \langle K^q_e(i)\rangle\right) n_0 dsec\theta_i\right]\} \\ &\cdot\left\langle |f_{pq}(-i,i)|^2\right\rangle\end{aligned} \quad (3)$$

where n_0 is the number of cylinders per unit volume and $f_{pq}(-i,i)$ and $K^{p/q}_e(i)$ are the scattering amplitude and extinction coefficient respectively. Similar to model I, the backscattering from the rough ground is modeled with I^2EM model. The α, β and γ angles are the Tait-Bryan angles. As cylinder orientation angles are non-correlated, the joint probability distribution function can be factored out as,

$$p(\alpha,\beta,\gamma) = p(\alpha)p(\beta)p(\gamma) \quad (4)$$

Due to symmetry of cylinders Euler angles can be used to describe cylinders by letting

$$\gamma = 0 \qquad \text{and} \qquad p(\gamma) = 1 \quad (5)$$

2.3. Ground data and input parameters of the models

The field surveys were conducted in the selected test sites in December, 2019 and March, 2021. The study area is located at the western slopes of southern Western Ghats in Thiruvananthapuram district of Kerala having different vegetation types. The measurements were taken by establishing plots of size 31.6×31.6m. Sampling plots were established in all the major vegetation types of the area viz. moist deciduous, semi-evergreen and evergreen forests and forest plantations namely acacia and eucalyptus. Measured biophysical parameters include, tree height, trunk diameter, soil moisture and species names. ALOS-2 L-band dual-pol SAR data acquired of March, 2019 has been used in the study. Input Parameters to the models include frequency, incident angle and polarization, soil moisture, correlation length, surface roughness, dielectric constant, tree height and trunk radius. Forest biophysical parameters were assumed to have remained unchanged during the survey period. Therefore, tree density, diameter at breast height, canopy height, soil moisture and vegetation water content were assumed constant. The input height of the vegetation stand in each plot was the median value of the heights in the respective plot.

2.4. Inverse problem for height Estimation

The estimation of trunk heights using a canopy scattering model can be stated as an inverse problem. In this study, Iterative optimization (IO) approach was used to retrieve heights. The iterative optimization is a popular technique for the inversion of ill-posed problems [13]. Let **Y** be the vector of output variables related to the vector of input variables **X** by the model **M** as **Y = M(Θ, X) +** ϵ, where Θ is the vector of model parameters. The inversion process determines X by minimizing a merit function S(X) for n number of observations by,

$$S(X) = \sum_{i=1}^{n} [Y_i - M(\Theta, X_i)]^2 \tag{6}$$

In general, this merit function is non-linear and is solved by classical optimization techniques, e.g., Nelder-Mead Simplex method [14]. The method starts with an initial guess of the variables and is iteratively updated while the merit function approaches towards a minimum. The minimization problem is re-written as a constrained non-linear multivariate scalar function. The range of acceptable height was constrained by 3 - 25m. In between these ranges, the values of X_i that minimize the merit function (using a non-linear L-BFGS-B algorithm [15]) are selected as the optimal result. For validation purpose, the modelled tree heights were compared with ground measurements at the study sites. One point from each vegetation type was used for fine tuning the forward model and the remainder of data used as independent validation points. The performance of the inversion was assessed in terms of the coefficient of determination (R^2) and root mean square error (RMSE) between estimated and observed tree heights. A vegetation stand height map was prepared from model II. To reduce the computing time in the optimization process, the ALOS -2 image was resampled to 100m pixel size and the non- vegetation areas are masked out in the process

3. RESULTS AND DISCUSSION

This section discusses the results of forest height retrieved using the models I & II with ALOS-2 data along with the validation of each using field measurements. Linear relationships between vegetation stand heights and polarizations of ALOS-2 data showed a relatively high R^2 value for HV polarization (R^2 = 0.26) in comparison to HH polarization (R^2 = 0.034). The validation of height estimated from model I with ground measured values resulted in a R^2 value of 0.47 with an RMSE of 4.01 m. See Fig. 1 for the regression plot.

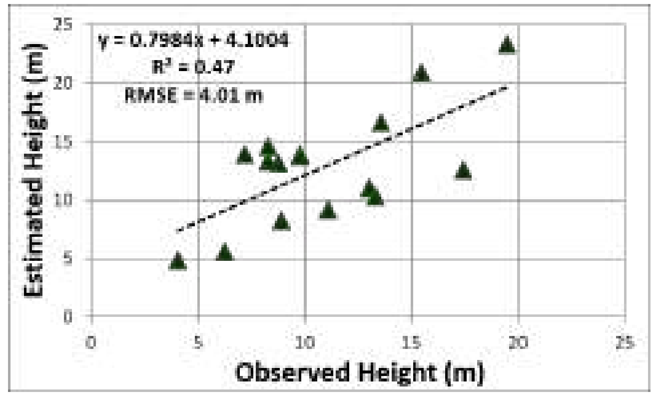

Fig. 1. Validation plot of tree height from model I with ground measured data

Whereas the retrieval accuracy has improved further using model II (See Fig. 2). Here, the R^2 value between the observed and the estimated height is 0.61 with a better RMSE value of 3.16 m. This shows that the predicted values from model II are more correlated to the field values. This makes the case for adding a trunk component to the model, instead of a homogeneous layer of spherical particles, to achieve a better accuracy in estimation of forest stand height. Fig. 3 shows the estimated tree height map obtained by model II inversion in the study area..

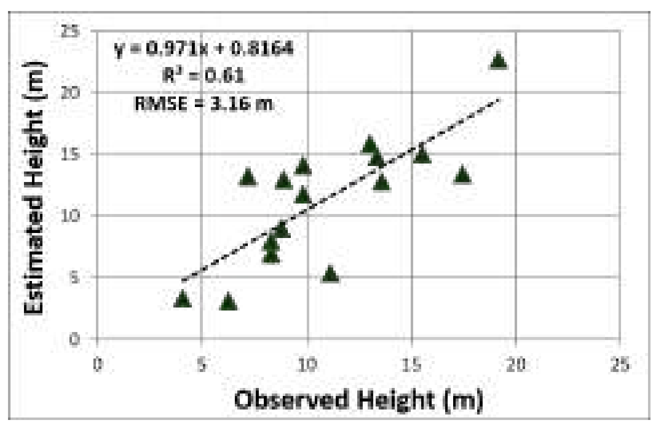

Fig. 2. Validation plot of tree height from model II with ground measured data

4. CONCLUSIONS

In this work, two polarimetric microwave canopy scattering models were compared for their accuracy in tree height estimation, which is a problem of paramount importance in forestry. The retrieved heights from the two methods were compared to the measured heights from the field. ALOS-2 L-band data at HH and HV polarizations were used in the study.

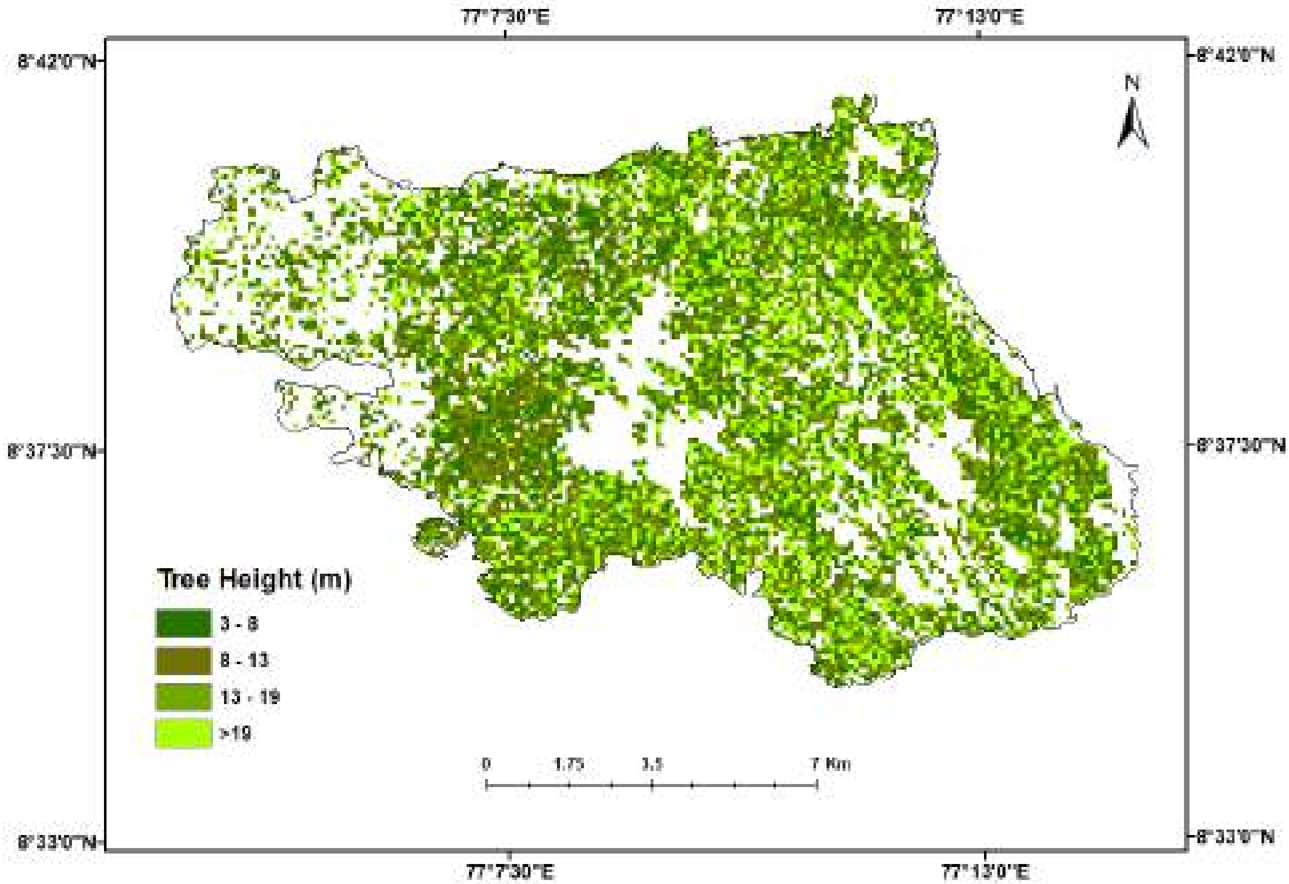

Fig. 3. Vegetation stand height map of the study area (100m pixel size).

The canopy models chosen were S^2RT model (model I) and dielectric cylinder model (model II), with a common I^2EM surface scattering layer. The Ground measurement data was collected from the tropical forests of Kerala in December, 2019 and March, 2021. Inversion methodology adopted was the Iterative Optimization (IO) method. Out of the two models, the highest correlation (R^2 = 0.61) and lowest error of estimation (RMSE = 3.16 m) were reported for model II. Results presented here demonstrate that adding the trunk layer into the canopy model improves the accuracy of forest biophysical parameter retrieval. Further, the study shows that the dual polarized SAR modes and in-situ measurements collected systematically can be adeptly employed to retrieve tree biophysical parameters from tropical forests. Adding the height component to the allometric model can improve the model efficiency in estimating AGB. Hence the predicted height values along with Diameter at Breast Height (DBH) in the allometric models can be used for estimating AGB of the study area. This constitutes part of an ongoing work from authors. Since the study involves complex physical modelling, a number of input parameters had to be fixed for running the model. Further, increasing the number and spread of the ground truth points in the rather inaccessible terrains of tropical Western Ghats was also a constraint. Addressing these issues and exploring options for multi frequency SAR data analysis encompassing future NISAR mission offers ample scope for updation of the study methodology.

5. ACKNOWLEDGEMENT

Authors thankfully acknowledge the funding support provided by Space Application Centre, ISRO, as part of L&S airborne PI Scheme.

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IEEE Catalog Number: CFP21U63-ART
ISBN: 978-1-6654-4249-7

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